Micromachined Tunable Optical Filters for Remote Sensing Applications

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Micromachined Tunable Filter Development

- Feasibility of low-order Fabry-Perot filter technology has been demonstrated and a variety of systems have been developed for both mid- and long-infrared applications

> Future development focus ⟶ increase compactness
> reduce complexity

- Microfabrication techniques can be used to fabricate completely solid-state filter assemblies, combining the mechanical advantages of micromachined structures and optical advantages of low-order Fabry-Perot imaging

- New applications become possible
  - ground-, air-, and spaceborne imaging systems
  - spectrometer on a chip
  - cryogenic cooling simplified

Background: PSI's AIRIS System

- PSI has successfully demonstrated MWIR and LWIR <u>A</u>daptive <u>I</u>nfra<u>R</u>ed <u>I</u>maging <u>S</u>pectrometer systems (3 to 5 µm and 8 to 14 µm)
- Fabricated using conventional methods
  - piezoelectric actuators
  - capacitive sensing
- Continuous Spectral Coverage over wide wavelength range (1 to 6 µm)
  - millisecond tuning times
  - common pixel registry
- Full spatial image at spectral resolution 1 to 2% λ
- Adaptively sample wavelengths to enhance scene contrast
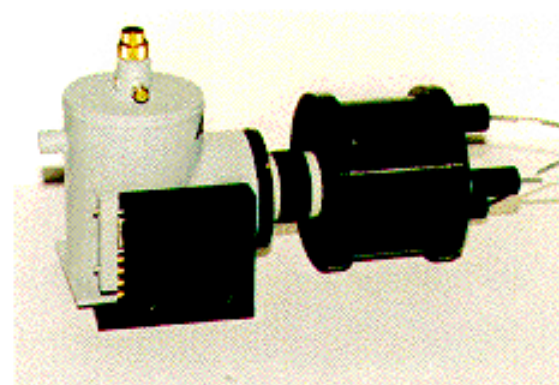
MWIR AIRIS with commercial InSb camera

- Demonstrated
  - optical quality and field uniformity over 7 x 9 deg FOV
  - spectral resolution and out-of-band rejection
  - high throughput - $A\Omega = 0.2$ cm^2-sr
  - portability, reproducibility, ruggedness
- Applications
  - fenceline and fugitive emissions monitor
  - tactical and strategic discrimination
  - compact intelligent remote sensing
  - transient event spectral imaging

Monochromatic image at 4.66±0.008 µm

Infrared Multi-Spectral Imaging Applications

<u>Science</u>

- Ground- and space-based astronomical observations
- Advanced laboratory instrumentation for infrared spectroscopy
- Compact spectrometers

<u>Industry</u>

- Hazardous waste site/fence line monitoring
    - site awareness
    - disaster assessment

- Rapid materials characterization
    - manufacturing and sorting (e.g., plastics recycling)
    - chemical and pharmaceutical process control

- Combustion gas sensing
    - emissions monitoring
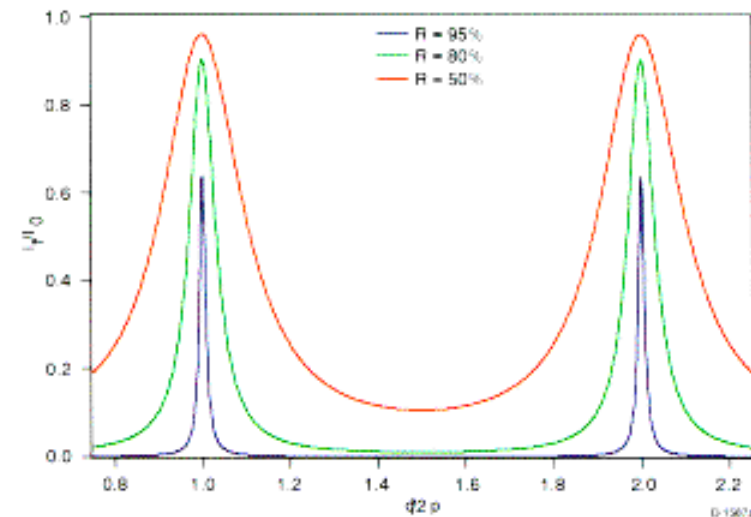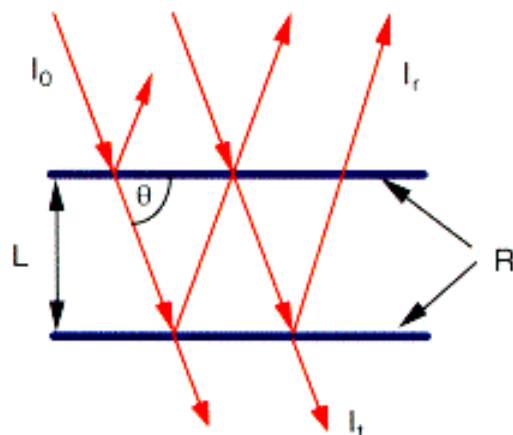   - sensor for control system

Etalon Basics

- Etalon transmission equation

$$\frac{I_t}{I_0} = \left(\frac{T}{1-R}\right)^2 \left[1 + \left(\frac{2F}{\pi}\right)^2 \sin^2\left(\frac{\delta}{2}\right)\right]^{-1} \qquad \delta = \frac{4\pi nL \cos(\theta)}{\lambda}$$

R = surface reflectivity
n = index of material between surfaces

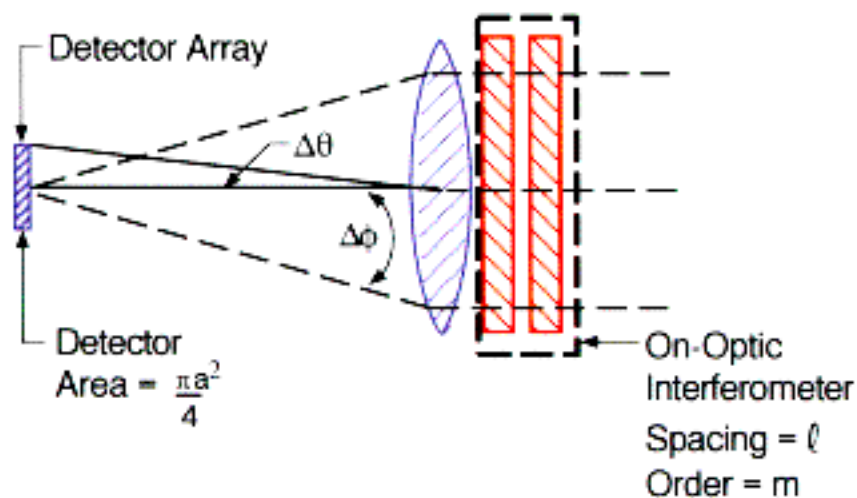Etalon finesse (F) is a measure of the sharpness
of the reflectivity fringes

Fringe spacing = free spectral range

$$\Delta\lambda = \frac{\lambda^2}{2nL} \qquad \Delta L = \frac{\lambda}{2}$$

Several factors determine etalon finesse
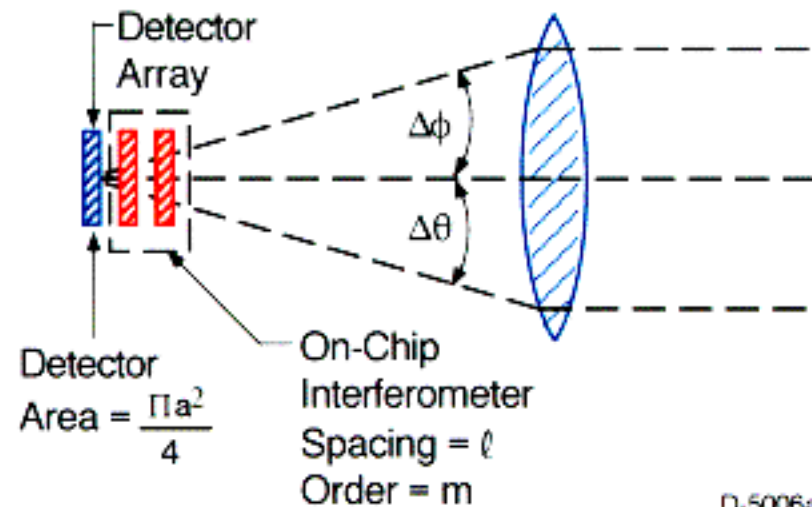— surface reflectivity, roughness, and parallelism

Fabry-Perot Filter Configurations

Filter-On-Optic

Detector Array

$\Delta\theta$

$\Delta\phi$

Detector
Area = $\dfrac{\pi a^2}{4}$

On-Optic
Interferometer
Spacing = ℓ
Order = m

D-5005az

Filter-On-Detector

Detector
Array

$\Delta\phi$

$\Delta\theta$

Detector
Area = $\dfrac{\Pi a^2}{4}$

On-Chip
Interferometer
Spacing = ℓ
Order = m

D-5006az

$$\text{Resolution} = \frac{\ell\Delta\theta^2}{(m+1)}$$

- Best combined spectral resolution and collection efficiency

- Arrays of micromachined filters can be used to achieve large apertures

$$\text{Collection efficiency} = \left(\frac{\pi a \Delta\phi}{2}\right)^2$$

- Compact, potential for very high level of integration

- f/# of collection lens limited by constraint on angular acceptance

Tunable Filter Performance Goals

Spectral Resolution:

$$R = \lambda/\Delta\lambda = 150 \rightarrow \Delta\lambda_{FWHM} \approx 25 \text{ nm at } \lambda = 4 \text{ } \mu m$$

Collection Efficiency:

$$A\Omega = 0.01 \text{ to } 0.1 \text{ cm}^2 \text{ sr} \rightarrow \Delta\theta = \pm 3 \text{ deg}, A = 1 \text{ to } 4 \text{ cm}^2$$

Tunability:

$$\Delta\lambda_{FSR} \approx 1 \text{ } \mu m$$

Out-of-Band Rejection:

$$< 1\% \text{ transmission for } \lambda > 3\Delta\lambda_{FWHM}$$

Cryogenic Operation:

$$T \sim 77 \text{ K}$$

Fabry-Perot Filter Optical Performance

Single Element Filter

Single $m = 3$ filter
w/ area = 1 cm^2; F=40; R=95%, A=1%

$R = 150$ ($\Delta\lambda_{FWHM} = 25$ nm)

$A\Omega = 0.02$ cm^2-sr

$\Delta\lambda_{FSR} = 1.0$ µm

Out-of-band rejection = 27%

Dual Element Filter

Stack $m = 3$ and $m = 9$ filters
w/ area = 1 cm^2; F=40; R=95%, A=1%
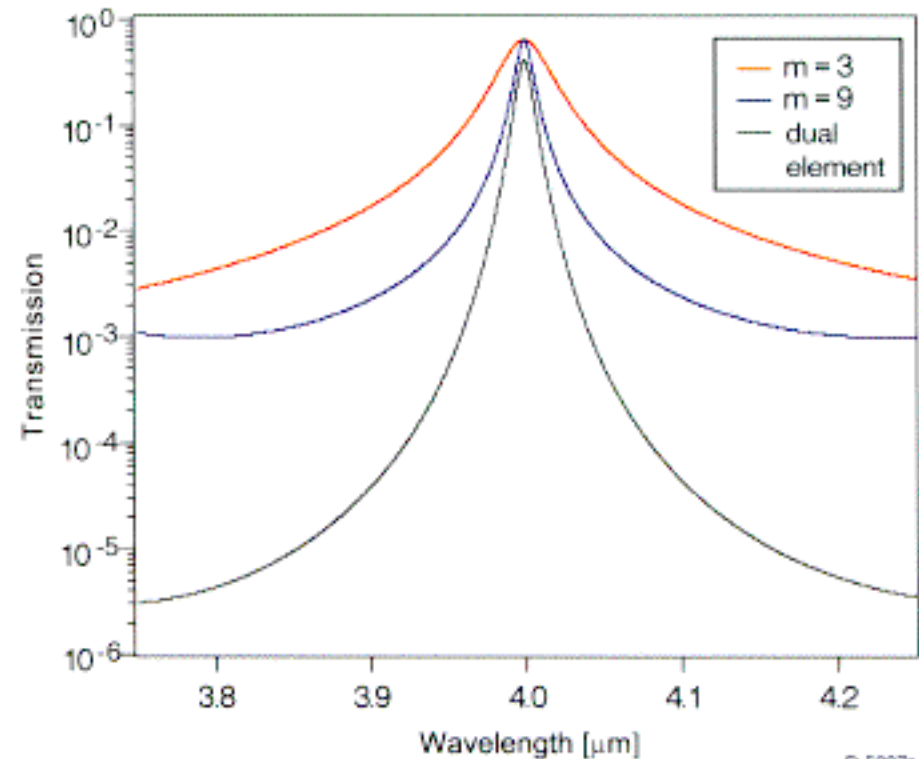
$R = 150$ ($\Delta\lambda_{FWHM} = 25$ nm)

$A\Omega = 0.01$ cm^2-sr

$\Delta\lambda_{FSR} = 1.0$ µm

Out-of-band rejection = <1%
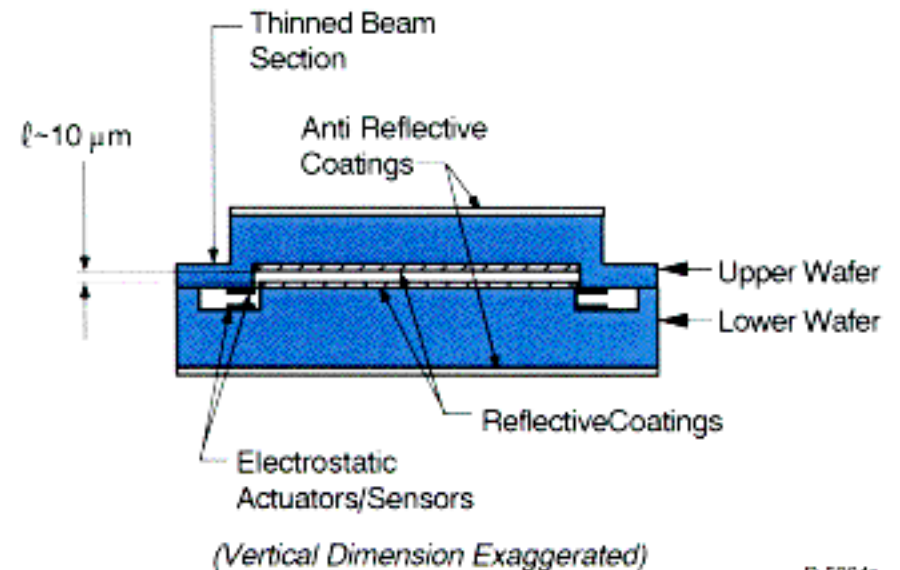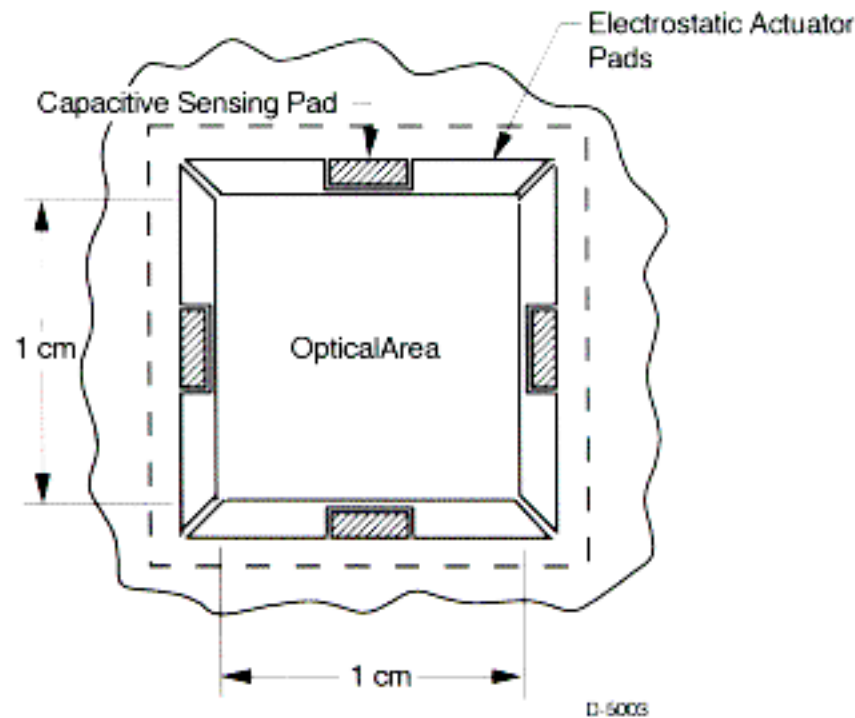

- Dual-element Fabry-Perot required to achieve <1% background transmission
- Single element filters may be suitable for some applications

Micromachined Tunable Optical Filter Concept

- Working with MIT on micro-fabrication process development
- Very compact to allow close coupling with camera array
- Single-crystal silicon construction for stable and predictable performance
- Integrated electrostatic actuation and capacitive sensing
  for adaptive tuning

Fabrication Process Features

Fabrication involves deep reactive ion etching and wafer bonding of single-crystal silicon wafers:

- Single-crystal construction
    - well-defined elastic properties
    - no residual stress
    - good optical properties in infrared

- Silicon-On-Insulator (SOI) wafers
    - upper and lower Si layers separated by SiO_2 layer
    - SiO_2 acts as etch stop, simplifying overall fabrication process
    - very uniform upper Si layer: large apertures, arrays
    - polished surfaces for good optical performance

- Reactive Ion Etching (RIE)
    - masking simplified compared to bulk micromachining
    - high aspect ratio structures: good area use efficiency

- Ge/SiO optical coatings
    - materials compatible with semiconductor fabrication processes
    - stress can be controlled through proper design
    - need to use low-temperature bonding

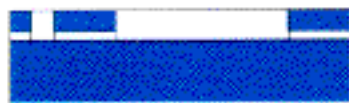# Simplified Fabrication Process
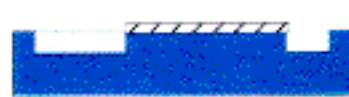
SOI Wafer

Plain
Wafer

Etch Optical Cavity & Vent

Etch Beam Deflection Clearance
Areas

Deposit Dielectric Mirror

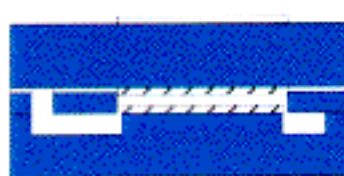Deposit Dielectric Mirror
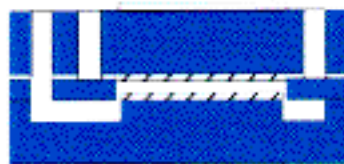
Deposit Anti-Reflection Coating

Deposit Anti-Reflection Coating

Bond Assembly

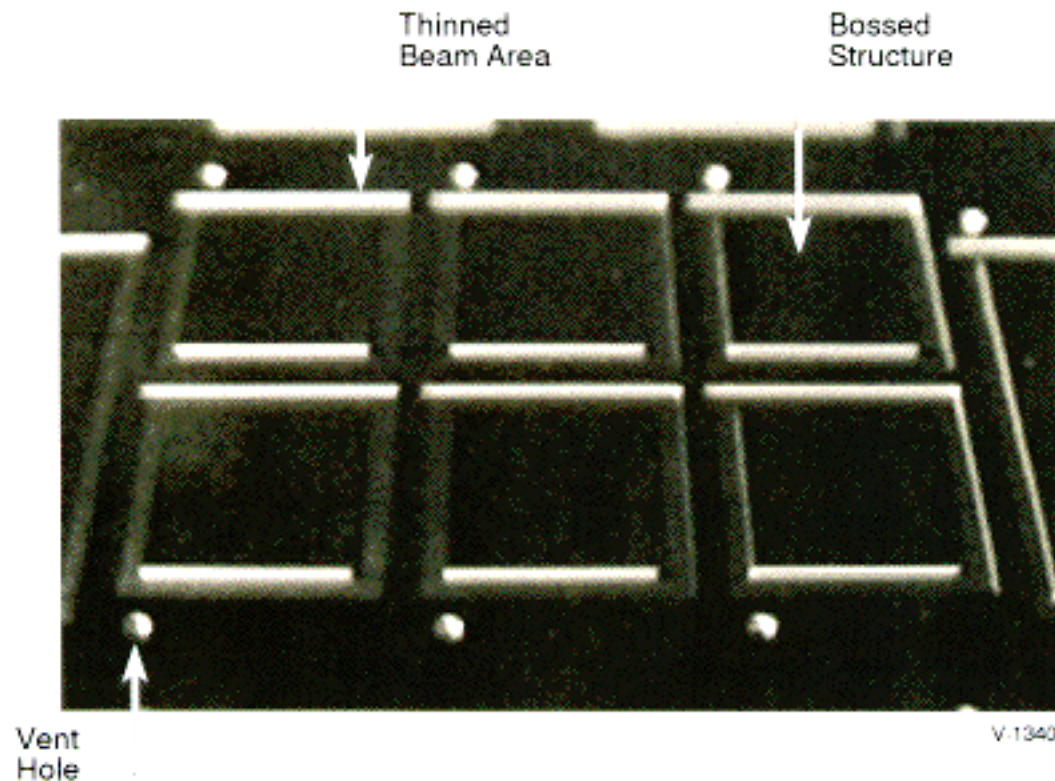Form Bossed Structure and Etch Through Vent

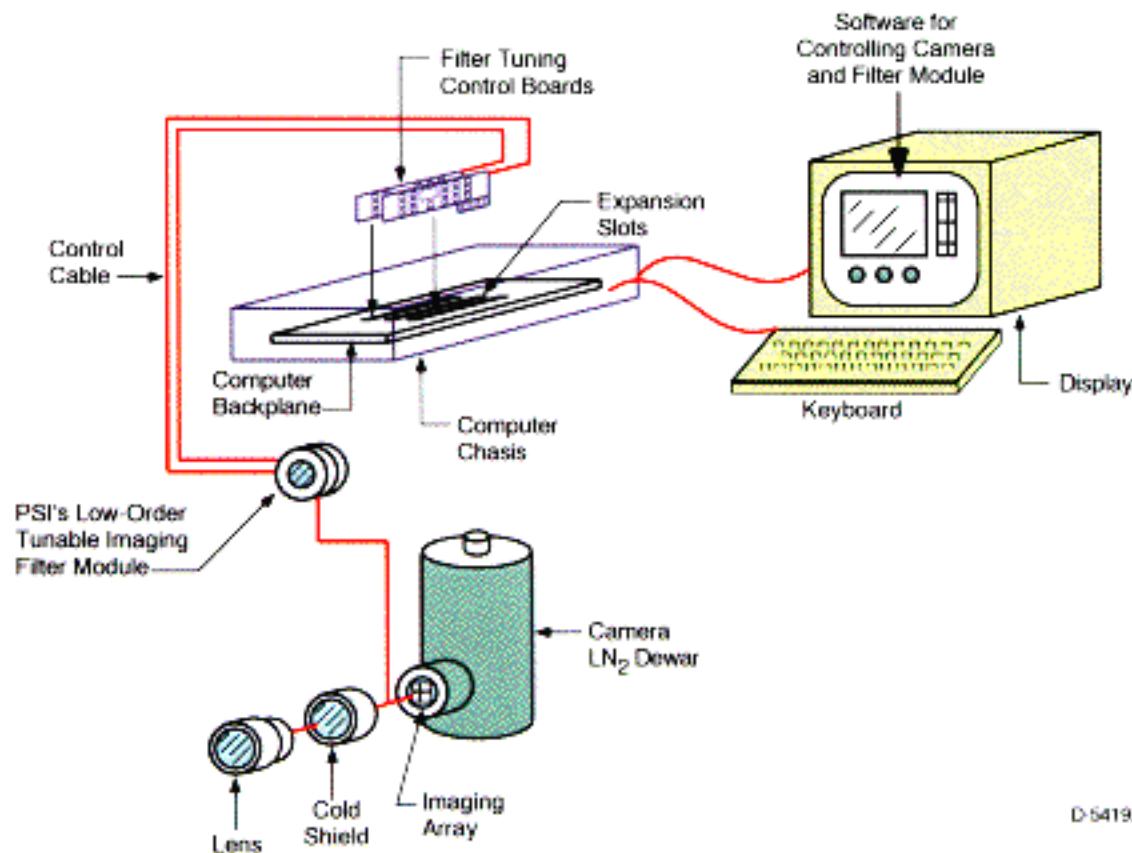D-5002z

Prototype Filter Array Fabrication

- Micromachined basic filter structure to demonstrate feasibility of fabrication process

- 3 x 2 array of 0.5 cm aperture filter structures
- Deep reactive ion etching ~ 300 µm deep structures
- High-temperature fusion wafer bonding (no optical coatings)
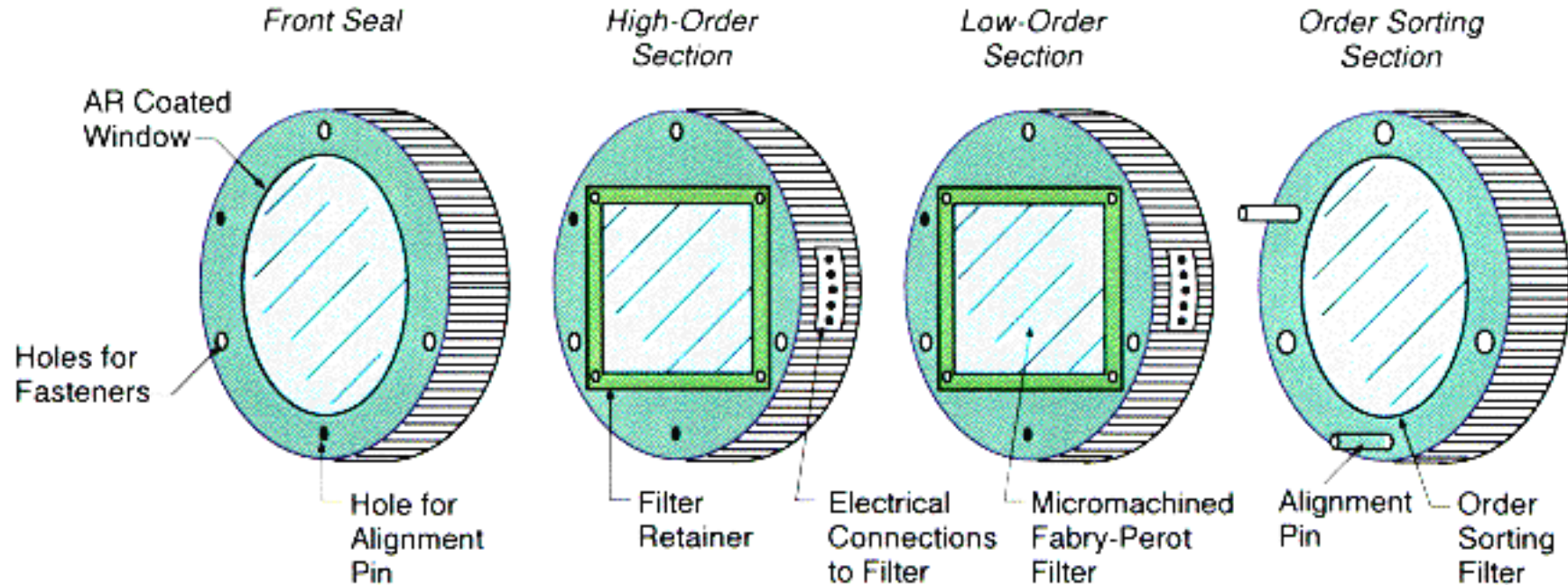
Multi-Spectral Infrared Imaging System

- Compact filter assembly integrated with camera

- Computer-based control system for filter tuning and image acquisition

- Board level filter control electronics which insert directly into computer expansion bus

Low-Order Fabry-Perot Imaging Filter Module

- High- and low-order micromachined filters in series
- Compact assembly to be integrated directly in front of a cooled camera array
- Compatible with cryogenic, vacuum environment of camera dewar

Summary

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- Basic tunable filter design completed

  - micromachined optical cavity with apertures ~1 cm

  - Ge/SiO optical coatings

  - integrated electrostatic actuators and sensors for tuning

- Optical coating performance successfully demonstrated

  - good reflectivity and transmissivity over 3 to 5 μm band

  - adequate stress cancellation achieved through proper coating design

- Fabrication process feasibility demonstrated

  - non-tunable structures without optical coatings completed

  - prototypes including optical coatings currently being tested